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GPS/INS AND PRECISION ANALYSIS OF THE NAVIGATION
PERFORMANCE

by

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Discussion on the Integrated Approach of the GPS/INS and Precision
Analysis of the Navigation Performance

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Abstract   This paper discusses on the advantages and
shortfalls of the integration of the 2 navigation systems, namely
the GPS and the INS, and then it discusses a method of integrating
them by use of the pseudo range and pseudo range-rate measurements
of the GPS-receiver to integrate GPS with INS. Because the
measurement errors of the GPS are all different, the numerical
simulation of the integrated navigation capability of a plane had
to be computed under different conditions of the differential
machines, and details of the accuracy analyses were also made
accordingly. The results showed that such integrated system of
navigation provided the accuracy which could not be achieved by
either the GPS or the INS alone. By integrating the differential
GPS receiver with the INS, the errors in position could be further
reduced. The integrated navigation thus opens up a new area of
application to be used for a plane to approach an airport for a
landing.

I. INTRODUCTION

The inertial navigation system of all the aircraft
facilities has a unique function to provide the accurate
communication information. However, the errors in position
will increase as time goes by. To overcome such shortcoming,
often other navigation facilities installed in the aircraft
are being used in tandem in order to obtain informations of
most superior quality, statistically speaking. The GPS as
the global positioning system can make accurate
determinations of 3-dimensional positions, speed and time,
but it cannot provide the needed information of the plane,
such as the signal to show the altitude of the plane or the
effects of the plane movements, in order to have its motion
tracked or traced. By integrating the INS with the GPS, one
can overcome this shortcoming, and form an ideal integrated
system. Furthermore, other traditional functions of the GPS
remain intact to continue its reconnaisance work and by use
of the differential method or capability of the ground
surface pseudo position to improve the reliability on the
accuracy of the position determination by the GPS.
Consequently, analyzing the accuracy of the integrated
navigation system, making accurate estimations and utilizing
the integrated system for some new functions all have
important significances.

II.   THE INTEGRATION METHOD OF GPS/INS

The integrating method basically can be classified into
2 kinds :

1.   By use of the GPS receiver (below, to be just called as
the GPS instruments) to obtain the information about
the position of a plane and its measured speed, and to
integrate them with INS (1).

The information sent out by the plane can be the
preliminary data to compute its position and speed with
respect to 4 stars (such method is commonly known as the
point-solution method), or it can be the estimated values of
the position and speed by use of "Carmey" filter wave
machine. The advantage of integration is to provide
additional navigational information, to simplify the
measuring procedure, and to reduce the filter wave
computation. But because the measuring equations are unable
to describe accurately the statistical and the correlative
characteristics of the noises relevant to the position and
velocity, and because of the effects on the filter wave, the
influence becomes even more prominent due to the difference
of the conditions in the satellite geometrical distribution.

2.   Utilization of the Pseudo Range and Pseudo Range-Rate
of the GPS instrument to integrate with the INS

The pseudo range and pseudo range-rate could be the
actually measured values (1,2) or they could be the
estimated values obtained from "Carmey" filter wave machine
(3). From the measuring equations, one can directly
describe the errors of the pseudo range and pseudo
range-rate to improve the integration and the result is less
affected by the difference in the satellite geometrical

distribution. But the parameter computation in the measuring equations is complicated and the computed values are relatively large.

III. SIMULATIONS OF THE NAVIGATIONAL FUNCTIONS OF THE INTEGRATION OF THE GPS WITH THE INS BY UTILIZING THE PSEUDO RANGE AND PSEUDO RANGE-RATE

By use of pseudo range and pseudo range rate, an example of the integration was worked out to simulate its functions ; the object to simulate is the integration of the plane platform type of the INS of an average accuracy which goes through the ground as the initial step and the GPS instrument of a single channel-multiple route reusable C/A. The INS navigation system assumes the horizontal coordinate system (the W-system) with a floating azimuthal direction for its coordinate system, the geographical coordinate system (the g-system) as the error equation coordinate system (4), and the star base of the GPS places the entire distribution of 18 stars under its consideration.

1. Introduction of simulation

(1) Integrating the states of filter wave. There are altogether 28 states which include 18 error-states of the INS of the position errors $(\delta L, \delta\lambda, \delta h)$ or $(\delta R_x, \delta R_w, \delta h)$, velocity errors $(\delta V_x, \delta V_w, \delta V_z)$, angular errors of the plane platform (Φ_x, Φ_w, Φ_z), bias in the acceleratometer $(\delta_{bx}, \delta_{by}, \delta_{bz})$, gyroscopic bias $(\varepsilon_{bx}, \varepsilon_{by}, \varepsilon_{bz})$ and the gyroscopic floating displacements in one Markovian Process $(\varepsilon_{mx}, \varepsilon_{my}, \varepsilon_{mz})$; 10 error-states of the GPS instrument which include 6 clock errors, phase error $(\delta\Phi)$, frequency error (δf), frequency variation error $(\delta\eta)$, and frequency error due to the velocity of the plane (δf_v); 4 bias in pseudo range measurements $(\delta\rho_{bi}, i=1,...,4)$. Among them the average

values of b_i , ε_{bi} and δ_{mi} $(i = X,Y,Z,$ which are the axial directions of the W-system) turned out to be zero and the average square-root errors of them are, respectively,

$$(E\{ \quad_i^2\})^{\frac{1}{2}} = 0.5 \times 10^{-4} g, \quad (E\{\varepsilon_{bi}^2\})^{\frac{1}{2}} = 0.01(^\circ)/h,$$

$$(E\{\varepsilon_{mi}^2\})^{\frac{1}{2}} = 0.005(^\circ)/h ,$$

For the INS error state equation and the GPS instrument clock error equation, see references (4, 5).

(2) The Measuring Equations. If the reference system is the g-system, the correlative formulas of pseudo range and pseudo range-rate are, respectively,

$$\rho_j = [(X_s - X_{sj})^2 + (Y_s - Y_{sj})^2 + (Z_s - Z_{sj})^2]^{\frac{1}{2}} + \delta\Phi + \delta\rho_{bj} + \delta\rho_{wj} \tag{1}$$

$$\dot{\rho}_j = \frac{1}{R_s}[(X_s - X_{sj})(\dot{X}_s - \dot{X}_{sj}) + (Y_s - Y_{sj})(\dot{Y}_s - \dot{Y}_{sj}) + (Z_s - Z_{sj})(\dot{Z}_s - \dot{Z}_{sj})] \tag{2}$$

$$+ \delta\dot{\Phi} + \delta\dot{\rho}_{wj}$$

where (X_s, Y_s, Z_s) and $(\dot{X}_s, \dot{Y}_s, \dot{Z}_s)$ are the coordinates and the rate changes of the coordinates of the carrier body with respect to the g-system, (X_{sj}, Y_{sj}, Z_{sj}) and $(\dot{X}_{sj}, \dot{Y}_{sj}, \dot{Z}_{sj})$ are the coordinates and the rate changes of the coordinates of the j-th star with respect to the g-system, R_j is the relative distance between the j-th star and the carrier, and $\delta\dot{\rho}_{wj}$ and $\delta\dot{\rho}_{wj}$ are, respectively, the white noises of $\dot{\rho}_j$ and $\dot{\rho}_j$. By use of the INS, the navigation coefficents $L_c, \lambda_c,$ h_c and V_{Nc}, V_{Wc}, V_{Zc} can be computed, and from the trajectory data of the satellites in the telecommunication messages of the GPS, one can obtain the computed distance $\dot{\rho}_{jc}$. If the measured value of the j-th star is

$$Z_j = \begin{bmatrix} \Delta\rho_j \\ \Delta\dot{\rho}_j \end{bmatrix} = \begin{bmatrix} \rho_{jc} - \rho_j \\ \dot{\rho}_{jc} - \dot{\rho}_j \end{bmatrix}$$

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Z_j not only has bearings with the GPS errors ($\delta\Phi, \delta\dot{\Phi}, \delta\rho_{jb}$, $\delta\rho_{wj}, \delta\rho'_{wj}$)' , but it is also related to the INS errors (δL, $\delta\lambda, \delta\bar{h}, \delta V_N, \delta V_w, \delta V_2$)! , and thus from it one can find out the measuring equation which has bearings with the state of the filter wave device.

If the frequency of the simulated filter wave is 2s, following the procedure-treating computations and by use of the method shown in reference (6), one can choose 4 stars as the useful ones.

(3) The orbit of the plane chosen by Simulation. The orbit of the plane is in 5 stages. The plane was accelerated for 200 s (a = 1.5 m/s^2)|, it climbed up for 100 s, flew horizontally at speed of 300 m/s for 3,400 s, then making a 180° turn-around, it flew horizontally back home. The total flight was about for 7,500 s.

2. The Results of Simulation

By use of pseudo range to compute the noise and bias, the following 3 kinds of integration simulation calculation were made :

(1) Simulation 1.   In simulating the basic error data, namely the average square-root errors of $\delta_{jw'}$, δ_{jb} and $\delta_{jw'}$, their values are as follows (1,7,8):

$$\delta_{jw} = 0.05m/s, \quad \delta_{jb} = 10m, \quad \delta_{jw} = 10m.$$
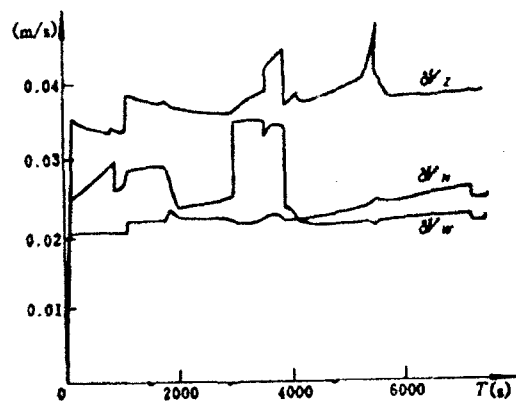
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Fig. 1   Simulation 1   The propagation curve of velocity
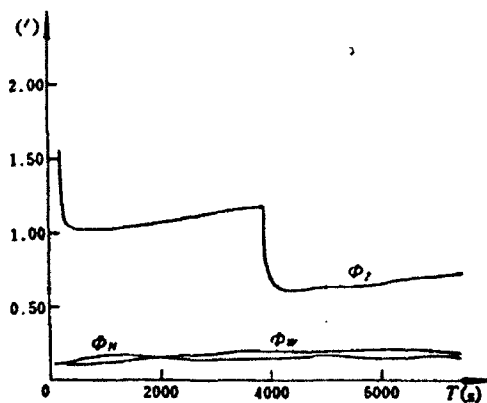   errors

Fig. 2   Simulation 1   The propagation curve of shape errors

The average square-root deviation of velocity errors, attitude errors and position errors from the results of simulation (namely the average square-root deviation of the errors after the corrections) as well as their propagation curves are all shown separately in Fig.1 - Fig.3 ; the geometrical accuracy factor GDOP of satellites and the expansion coefficients of the position errors of Northwest Sky NDOP, WDOP and VDOP propagation curves are shown in Fig. 4. The abrupt change in Fig. 4 was due to the replacement of satellites.

(2) Simulation 2.   When selective availability (SA) was assumed for the C/A ratio in America, the bias in pseudo range increased.   Simulation 2 chose δ_{pb} = 30 m (8), and simulation was affected by SA. The results of the simulation were similar to those from simulation 1, if position errors were increased slightly.

(3) Simulation 3.   A simple recognition of the differential GPS could entirely compensate for bias of the pseudo range.   Therefore if δ_{pb_i} = 0, the integration between the simulated differential GPS and the INS was effective. As compared to Simulation 1, the position errors went down slightly.
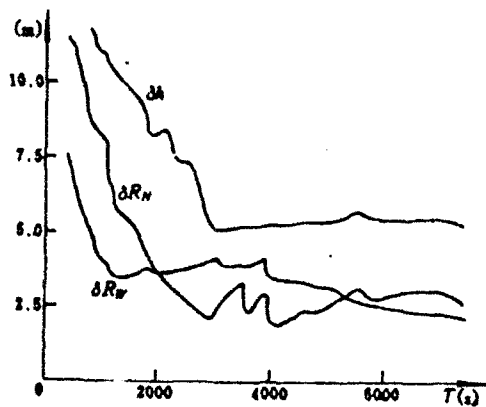
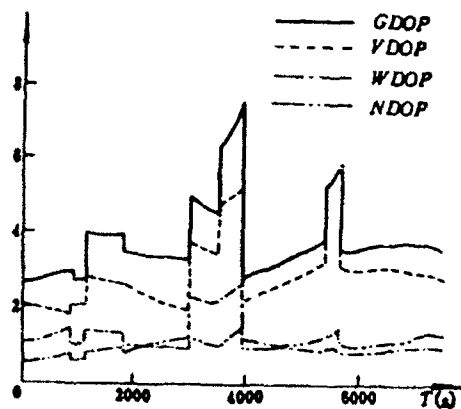Fig. 3 The propagation curve of position errors in
simulation 1

Fig. 4 The propagation curve of the expansion coefficients
of position errors in simulation 1

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IV. THE ACCURACY ANALYSES OF THE SIMULATED RESULTS

1. From the results of simulation 1 and simulation 2 to estimate the accuracy analyses of position errors and velocity errors, the estimated accuracy of position errors and velocity errors turned out to be pretty high, and the reasons seem to be as follows :

(1) The results of a direct integration of the highly accurate GPS pseudo range and pseudo range rate with either the position error or the velocity error of the INS. By use of a simplified situation one can analyze the declining rate of the INS's position errors. Suppose a system is integrated only with the pseudo range, and from the GPS instrument one can directly measure the 3 coordinates of the distance between a satellite and the carrier in the g-system. The measurement error is the white noise, and the average square root error is δ_{pi} (i = N, W, Z). If one neglects the clock error of the GPS instrument, and under the condition of non-diagonal elements of the estimated average square root error matrix P (k-1) of the filter wave device, one can obtain the approximate formula for the estimated average square root error $P_{\delta R_i}(k)$ (i=N,W,Z) of the position error at time k as follows :

$$P_{\delta R_i}(k) = P_{\delta R_i}(k / k - 1)\delta_{pi}^2 / (P_{\delta R_i}(k / k - 1) + \delta_{pi}^2) \tag{4}$$

The above expression shows that $P_{\delta R_i}(k) < \delta_{pi}$. Since the frequency of the filter wave in general can be assumed to be 1 - 5 s, and because $P_{\delta R_i}(k/k-1)$ cannot be too much greater than $P_{\delta R_i}(k-1)$, one can approximately recognize

$$P_{\delta R_i}(k / k - 1) = \delta_{pi}^2 > P_{\delta R_i}(k - 1)$$

Indeed $P_{SRI}(k) = \frac{1}{2}\delta_M^2$. After several estimations, one can let $P_{SRI}(k) < \frac{1}{2}\delta_M^2$. . The reason is this. If the estimated state is in the condition capable of being directly measured, "Carmey" filter wave utilizes all the timely measured values and thus it can filter out all the noise. Also it is because as shown in Reference (7) the filter wave equipment can filter out 2/3 of the measurement noise.

(2) The results of double integration of the pseudo range and pseudo range rate of the GPS with both the position error as well as the velocity error of the INS. By use of the GPS pseudo range to integrate with the INS, it not only improved the position error but because the pseudo range also has the capacity to observe the velocity error it could improve the velocity error as well. By use of the GPS pseudo range rate to integrate with the INS, beside improving the velocity error, it could also suppress the increase of the position errors. To prove the above mentioned analyses, a supplementary simulation was carried out on the integration only by the pseudo range. The results showed that accuracy in the estimation of the position error had gone down, but for the velocity error it definitely had the effectiveness of the estimation, and thus it explains that the double integration can lower both kinds of errors further down by one step.

(3) The integration enables the pseudo range bias to get estimated. In analyzing the observability of the system, one can see that the pseudo range bias is an observable quantity. The simulated results showed that as the times of estimations increased, the average square root of the pseudo range bias went down from 10 m to around 3 m, while bias of 30 m could go down to 7 - 8 m. This is a great effect in suppresing the measurement errors of the

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pseudo range extensively. Such quality to rely heavily on the GPS instrument is not appropriate.

(4) Integration can suppress unfavorable effects of the satellite geometrical distribution. As widely known, one can use GDOP to describe the influence of the geometrical distribution of satellites on the point-solution method in making position determinations. Below, analysis will be made with one simplified situation. Suppose that a satellite is on the same horizontal plane as the carrier, and one can neglect the clock error, just assuming the GPS measurement error as a white noise and the average square root deviation σ_{pw}. Now the pseudo range of the GPS is integrated with the INS and then the simplified equation for the position error of the INS

$$\delta \dot{R}_N = W_N \cdot \ \delta \dot{R}_w = W_w \qquad (5)$$

where W_N and W_w are the white noise. The distances of the carrier to the 2 stars were (ρ_1 and ρ_2) while those computed by the INS were (ρ_{c1} and ρ_{c2}), and the measured values were the differences between these 2 sets of values; that is,

$$Z = \begin{bmatrix} \rho_{c1} & - & \rho_1 \\ \rho_{c2} & - & \rho_2 \end{bmatrix} = \begin{bmatrix} cos\theta_1 & - & sin\theta_1 \\ cos\theta_2 & - & sin\theta_2 \end{bmatrix} \begin{bmatrix} \delta R_N \\ \delta R_w \end{bmatrix} + \begin{bmatrix} \delta \rho_{w1} \\ \delta \rho_{w2} \end{bmatrix} \qquad (6)$$

where θ_j $(j = 1, 2)$ is the azimuthal angle of the line which connects the j-th star to the carrier. To approximate $\Phi = I$ (I is the unit matrix), it becomes the transformation matrix after dispersing. Neglecting estimated average square root error matrix P(k-1) non-diagonal elements and going through the solution of the Carmey filter wave equation, one can get

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the average square deviation of the horizontal errors at time k as follows :

$$\sigma_H = (P^{11}(k) + P^{22}(k))^{\frac{1}{2}} = \frac{\sqrt{2}\,\sigma_{\rho w}}{\cos\theta}\left[\frac{1 + P_{12}\sigma_{\rho w}^2}{1 + (P_{12} + P_\theta)\sigma_{\rho w}^2}\right]^{\frac{1}{2}} = \frac{\sqrt{2}}{\cos\theta} K\delta_{\rho w} \qquad (7)$$

where $P^{ii}(k)(i=1,2)$ is the i-th diagonal elements of P(k) matrix. And with $\theta = (\theta_1 - \theta_2) - 90°$,

$$P_{12} = \frac{P_1 + P_2}{2P_1 P_2}, \quad K = \left[\frac{1 + P_{12}\sigma_{\rho w}^2}{1 + (P_{12} + P_\theta)\sigma_{\rho w}^2}\right]^{\frac{1}{2}}, \quad P_\theta = P_{12} + \frac{\sigma_{\rho w}^2}{P_1 P_2 \cos\theta} + \frac{1}{P_1 P_2 \cos\theta}$$

$$[P_1(1 + \sin^2\theta - \sin^2\theta_1 - \sin^2\theta_2) + [P_2(1 + \sin^2\theta - \cos^2\theta_1 - \cos^2\theta_2)] \qquad (8)$$

where P_1 and P_2 are 2 diagonal elements of $P(k/k-1)$ In equation (7), the factor $\sqrt{2}/\cos\theta$ is the geometrical accuracy factor of the 2-dimensional position determining system. When $\theta_1 - \theta_2 = 90°$, namely $\theta = 0$, the geometrical distribution is the best ; that is,

$$P_\theta(\theta = 0) = P_{12} + \delta_{\rho w}^2 / P_1 P_2 = P_{\theta min} \qquad (9)$$

$$K(\theta = 0) = \left[\frac{1 + P_{12}\sigma_{\rho w}^2}{1 + 2P_{12}\sigma_{\rho w}^2 + \frac{\sigma_{\rho w}^2}{P_1 P_2}}\right]^{\frac{1}{2}} = K_{min} < 1 \qquad (10)$$

When one looks at the contents of K, one sees that it represents "Carmey" filter wave which was at the estimated base, namely the k-th estimated effect. When $\theta = 0$, the estimated effects and the 2 horizontal directions (N, W) all had the same estimation effects from the independently measured values. When $\theta \neq 0$, if the approximation allows $P_1 = P_2$, then from formula (8) and (9), $P_\theta > P_\theta min$, and always $K < K_{min}$. To explain $\theta \neq 0$, "Carmey" filter wave can also suppress any unfavorable influence from the satellite distribution. A similar analysis on the integration with the velocity reached the same conclusion.

Although the above analysis was made by a simplified 2-dimensional situation, yet the results can be extrapolated to the actual integrated situations of the GPS and the INS. The result of simulations confirmed such characteristics; that is, although the velocity error and position error both

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receive the GDOP influence, but the influence is relatively small. Below, the accuracy of the GPS instrument navigation and those of various integrated navigations are all shown in the table for comparisons. Among them, there are 2 kinds, namely the GPS instrument navigation point-solution method and the filter wave solution method. In the point-solution method, the coefficient of expansion HDOP and VDOP was used to calculate the navigation accuracy, while the filter wave solution method filtered out 2/3 of the measurement noises, and by utilizing this effect it can calculate the navigation accuracy. The integrated accuracy used the last stage of the simulated flight as its accuracy. It also used HDOP = 1.6, VDOP = 2.7, $\sigma_{\rho b}$ = 10 m (30 m), $\sigma_{\rho w}$ = 10 m, and σ_{jw} = 0.05 m/s. From the table, one can easily see the effects of improvement in the navigation accuracy due to integrations.

Table

② 不同组合和解法 \ 均方差 误差类别	位置误差 (m) ①			速度误差		
	水平	垂直	总误差	水平	垂直	总误差
GPS 机点解法	22.63	38.18	44.39	0.080	0.135	0.157
GPS 机滤波解法	16.87	28.46	33.09	0.027	0.045	0.053
③ 差分 GPS 机滤波解法	5.33	9.00	10.46	0.027	0.045	0.053
基本 GPS／惯性组合(仿真 1)	3.54	5.83	6.82	0.036	0.037	0.052
大偏置 GPS／惯性组合(仿真 2)	3.64	6.01	7.03	0.036	0.037	0.052
差分 GPS／惯性组合(仿真 3)	1.51	2.72	3.11	0.036	0.037	0.052

(1) Classifications of Errors   Position Errors (m)
                    Velocity Errors

(2) Different kinds of Integrations and Solution Methods
    Average Square Root Deviation   Horizontal   Vertical
    Total Error   Horizontal   Vertical   Total Error
(3) The GPS instrument point-solution method
    The GPS instrument filter wave solution method

The differential GPS instrument filter wave solution method

Integration of Basic GPS/INS (Simulation 1)

Integration of GPS with large bias/INS (Simulation 2)

Integration of differential GPS/INS (Simulation 3)

2.   Attitude Error Estimation Accuracy. When the INS is integrated with the GPS at the initial condition, it can only suppress the increase of the horizontal error-angle with respect to the plane platform. However, there always exists the space-to-air aiming capacity (9) in such kind of integrations, and consequently the estimating action of this kind of integration under the flight condition of an airplane toward the azimuthal error is clear. To explain Fig. 2, going through the horizontal acceleration and the 180° Turn-around, the azimuthal error would decline from 3' to 0.5 - 0.7', which is very good.

3.   The integration unequally improves the original errors of the INS and the clock errors of the GPS instrument. In them, using the vertical acceleration to compute bias and making an estimation of the error which is sensitive to the clock acceleration are especially noticable. The reason is obvious. Improving the original errors is more advantageous when the GPS signal is interrupted, and in this case the functions of the INS are improved.

It needs some explanation if one considers the error in the movement of the GPS instrument or when one uses a stepping-down wave machine. The above-mentioned filter wave effect receives a constant influence.

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V. CONCLUSION

1. When the GPS instrument made a double integration with both the position and velocity of the INS, such integration made the bias of the GPS pseudo range observable, and it could also suppress the effects of GDOP, and therefore the estimation effect utilizing the integration of the pseudo range and pseudo range rate of the GPS with the INS was good.

2. The integration allowed the INS to possess the space-to-air aiming capability. Thus when a plane was accelerated and turned around, it could clearly make an estimation of the INS azimuthal error-angle. The results from simulation explained that the error could go down to below 1'.

3. After the GPS instrument integrated with the INS of only an average accuracy, the position error of the last stage of the flight according to the simulation was already about 7 m. If the differential GPS was used to integrate with the INS, the error could even go down to around 3 m, and moreover the main component of the errors was the vertical error component and therefore if the system expressed altitude in the integrated radio, the total position error could even be reduced at lower altitudes. Such kind of position accuracy is what the aircraft navigation craves for. Consequently, this integration system can be expected to open up a new application area to let airplanes make automatic entry to an air-field for a landing.

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